Shape Effect Related to Crystallographic Orientation on Deformation Behavior in Copper Single Crystal

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INTRODUCTION

The deformation behavior of single crystals is influenced by several factors, such as purity, crystallographic orientation, temperature, size, shape, and surface condition, etc.[1,2]. The size and shape of the crystal can especially have a significant influence on the deformation behavior. Many studies on crystals of similar orientation and purity show distinct differences [3,4], which can only be accounted for by the variation of glide path-length due to changes in size and shape of the sample. But it has been commonly believed that the initial operative slip system depends only on the initial crystallographic direction of the tensile axis and not on the glide path-length in samples [5-7].

This paper describes an investigation of the shape effect related to crystallographic orientation on deformation behavior in pure Cu single crystals by scanning electron microscope and an *in-situ* reflection Laue method using synchrotron radiation. The changes in crystallographic orientation of the single crystals during deformation were measured by the reflection Laue method that is suitable for *in-situ* observation. We examined two types of samples having the same orientation of tensile axes and an alternate crystallographic orientation in the direction of width and thickness of the sample. The two samples show different characteristics of deformation behavior, such as activated slip systems, movement of tensile axis, and mode of fracture.

EXPERIMENTAL PROCEDURE

The material used in the present study was 99.999% single-crystal copper. A tensile sample having a gauge length of 12 mm and a cross-section of 4.6-mm width and 1.0-mm thickness was prepared by spark-erosion cutting. After mechanical polishing, the sample was annealed in vacuum at 800 C for 72 hours and chemically polished to remove the damaged and oxidized surface layer formed during the mechanical polishing and heat treatment. From the procedure for sample preparation above, two tensile samples were prepared. The two samples had the same crystallographic orientation of tensile axis but had an alternate crystallographic orientation in the direction of width and thickness of the sample.

The synchrotron radiation source of the beamline 7.3.3 at the Advanced Light Source was employed for the *in-situ* reflection Laue experiment. The sample was elongated in steps of 0.45 mm by a tensile device mounted on a 2-circle goniometer. The focused x-ray beam size on the sample was 300 μm $\times$ 300 μm. Laue patterns were collected at each elongation step using white radiation and a x-ray CCD camera. The exposure time for each Laue frame was 1 sec. Two load cells attached to the left and right side of the sample grips measured the applied load on the sample. The strain rate was 3.7×10^{-4} sec^{-1}.

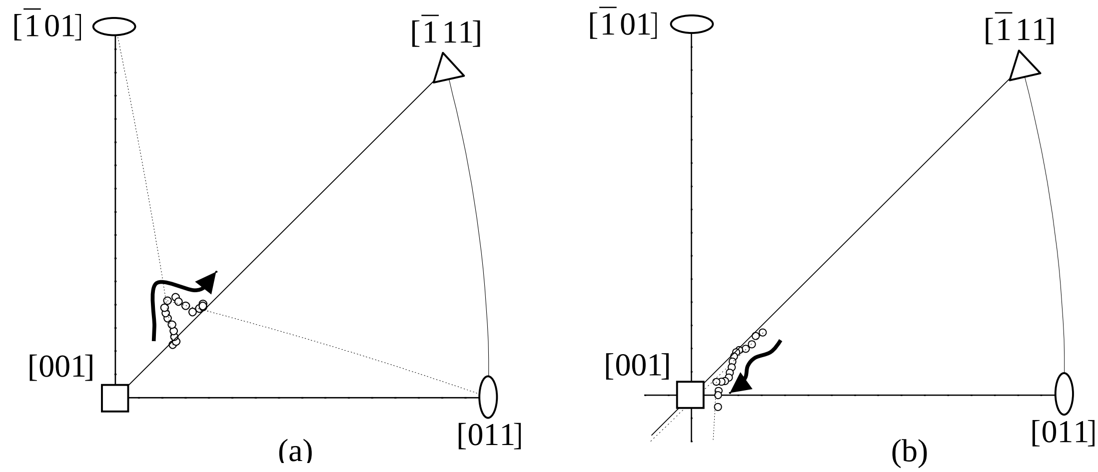

Figure 1. Tensile axis movement in the standard triangle. (a) sample A; (b) sample B.

RESULTS AND DISCUSSIONS

Stereographic projections of copper single crystal are shown in Fig. 1 where the initial orientation and the following rotations of the tensile axis were determined for each sample. All samples were uniaxially elongated until the point of fracture. According to classical deformation theory, the initial operative slip system is determined only by the initial crystallographic orientation of crystal relative to the tensile axis. The Schmid factor is the main item to determine the initial operative slip system in single-crystal tensile experiments [5]. If the crystallographic orientation of the tensile axis is located near the symmetry line connecting the [001] and [111] axes on the stereographic projection, then the classical theory predicts that two slip systems, BIV and CI, can be operating simultaneously. Here the BIV and CI slip systems represents $(111)[\bar{1}01]$ and $(\bar{1}\bar{1}1)[011]$, respectively.

With the exception of alternative crystallographic orientations in the directions of width and thickness, the samples A and B are in the same deformation condition from the viewpoint of the

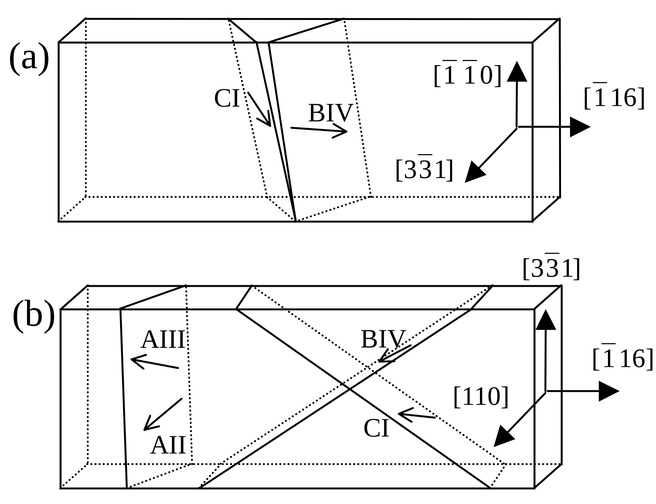

Figure 2. Schematic diagram of the crystallographic orientations of samples and the slip plane and slip direction before deformation. (a) sample A; (b) sample B.

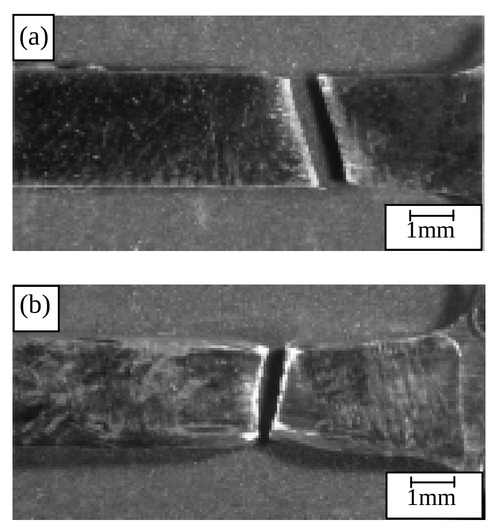

Figure 3. Photo image of deformed Cu single crystal. (a) sample A; (b) sample B.

classical deformation theory. However despite the similarity of initial crystal orientations of the samples, vastly different deformation behaviors were observed. In sample A, the rotation of tensile axis showed an oscillatory motion (Fig. 1a) as the classical theory predicted. The oscillatory motion means that the BIV and CI slip systems were activated simultaneously as initial operative slip systems. But the tensile axis of sample B moved in the opposite direction, which indicated that the operated slip systems were different between the samples A and B despite the similarity of initial crystal orientations of the two samples. To explain this unexpected result from the sample B, we took into account glide path-lengths of all the slip systems as well as the Schmid factor. Figs. 2 (a) and (b) show the expected operating slip systems in the samples A and B, respectively. The Schmid factors for BIV and CI slip systems are the largest in all the 12 possible slip systems of the sample. The Schmid factors of the AII and AIII slip systems are about 95% of those of the BIV and CI slip systems. Here the AII and AIII slip systems are $(\bar{1}11)[101]$ and $(\bar{1}11)[0\bar{1}1]$, respectively. If the AII and AIII slip systems are activated simultaneously as initial operative slip systems, the predicted movement of tensile axis can result in the Fig. 1(b). The calculated glide path-lengths of the AII and AIII slip systems are about 2 times larger than those of the BIV and CI slip systems in the early deformation stage of the samples examined. Therefore it is concluded that the Schmid factor does not solely determine the initial operative slip systems: the glide path-length may be another important factor to determine the initial operative slip systems.

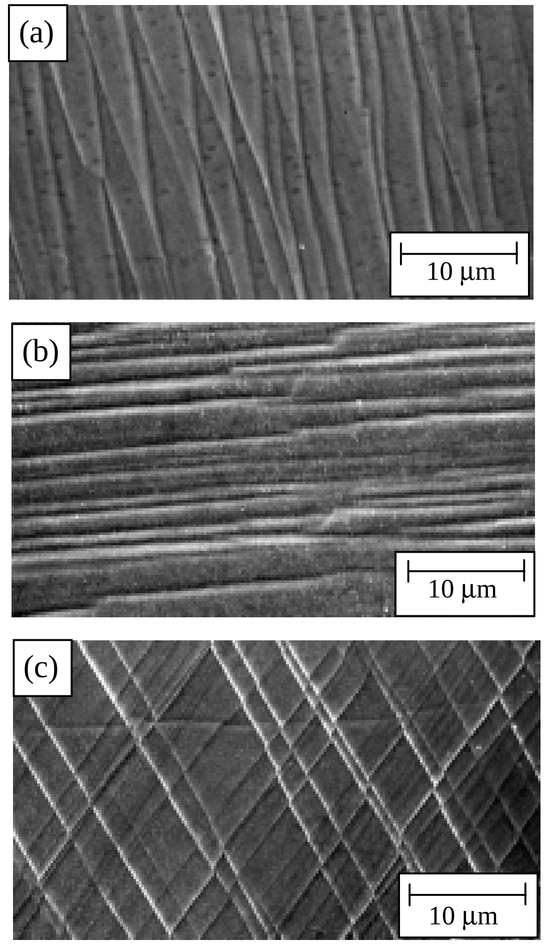

Figure 4. Slip line Images of scanning electron microscope. (a) sample A; (b) sample B in the centered region; (c) sample B in the boundary region.

Figs. 3 (a) and (b) show optical micrograph of sample A and B, respectively. The fracture mode of the sample A is shear with shearing angle of about 73 degrees (Fig. 3a). This shearing fracture of the sample A occurs as the result of extensive slip on the active slip systems, BIV and CI. The fracture mode of the sample B is not clear, as shown in Fig. 3(b). There are two possibilities: one is the shearing fracture due to AII and AIII slip systems and the other is necking due to multiple slip. When fracture occurs, the tensile axis is near the [001] direction. Therefore it is still unclear which is the origin of fracture.

Fig 4 shows scanning electron microscope images of the samples. It should be mentioned that the method of slip line measurements suffer from the disadvantage that they are essentially surface observations and describe the slip pattern at the surface only. However, since the height of slip lines is proportional to the number of escaped dislocations, these slip lines may be thought to describe adequately the behavior of the operated slip systems inside the bulk [2]. The observed slip lines of sample A show the characteristic shapes and agree with previous prediction in Fig. 2(a). The two different slip lines have an intersection angle of less than 10 degrees. The measured angle of the slip lines is slightly larger than that calculated result from the initial orientation. In sample B, we can observe the characteristic slip lines that result from different slip systems. The shape of slip lines in the central region accords with the result of Laue diffraction. But the shape of slip lines in the boundary region displays another feature. Because of the shape effect of sample, the glide path-length in the boundary region is much shorter than that in the central region. The measured angle between two slip lines is 65 degrees and is nearly the same as the calculated value. Therefore it is concluded that these slip lines are caused by the BIV and CI slip systems.

CONCLUSIONS

The deformation behavior of pure copper single crystals has been investigated by scanning electron microscope and an *in-situ* reflection Laue method using synchrotron radiation. Although the samples have the same orientation of the tensile axes besides the alternative crystallographic orientation in the directions of sample width and thickness, they show very different deformation behavior. In sample A, the BIV and CI slip systems are activated and shearing fracture occurs. In sample B, the AII and AIII slip systems are mainly operated in the central region but the BIV and CI slip systems are activated in the boundary region due to change of glide path-lengths. The first operative slip system should not be necessarily the one with the highest resolved shear stress. The condition of a minimum glide path-length through single crystal should be taken into account as one of the factors to determine the operative slip system.

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